OptElec: an Optimisation Software for Low-Thrust Orbit Transfer Including Satellite and Operation Constraints

7th International Conference on Astrodynamics Tools and Techniques, DLR, Oberpfaffenhofen – Nov 2018

DEFENCE AND SPACE

Slim Lococche - Mission Analysis and Trajectory Optimisation - slim.lococche@airbus.com
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AIRBUS

Outline

- Introduction
- Software Requirements
- OptElec
- Study Cases
- Conclusions

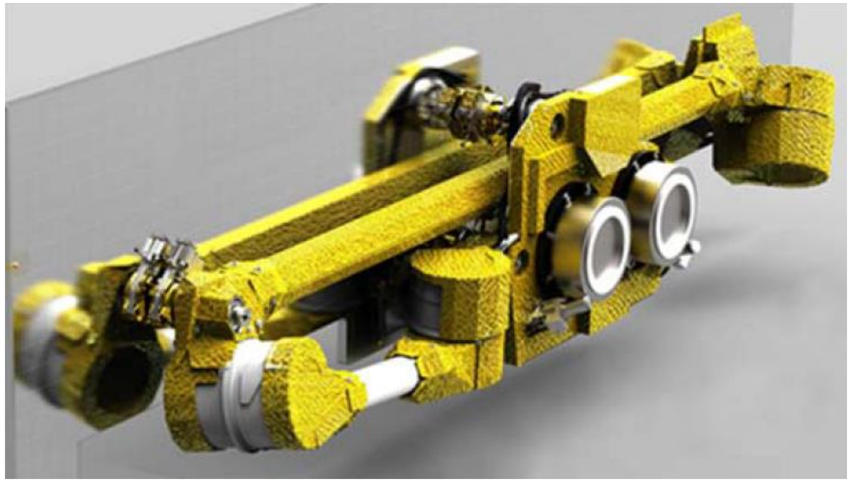
Introduction

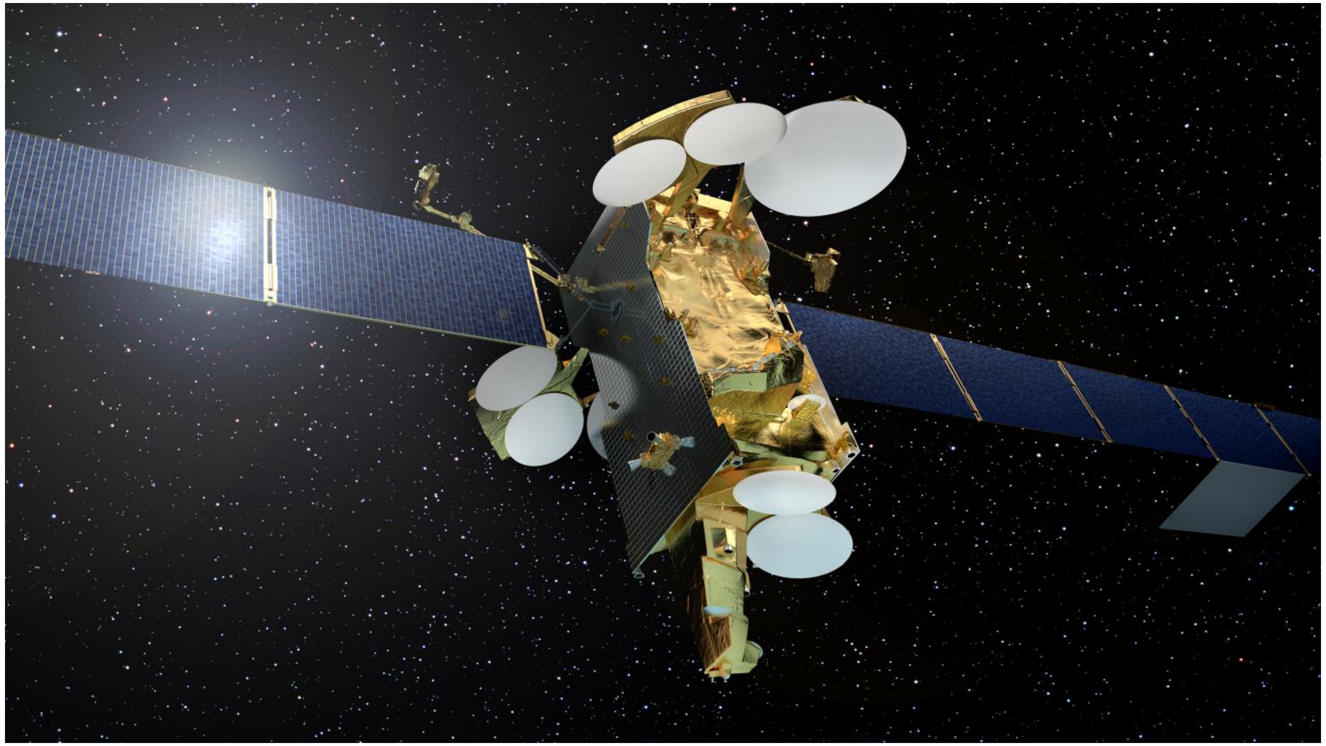
Context – Electric Orbit Raising (EOR) at Airbus Defence and Space

- Low-thrust electric propulsion (EP) for telecom satellites → mass savings
  - Smaller/cheaper launchers for a given payload
  - Larger payload

- EP already used but for station-keeping

- Airbus Defence and Space: E3000e satellites
→ Full electric transfer





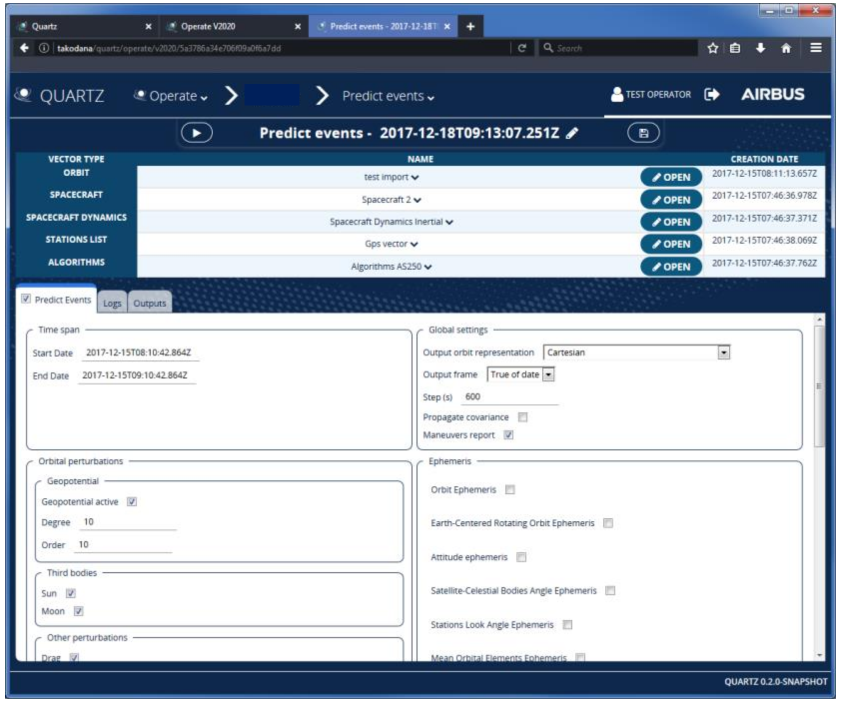
Introduction

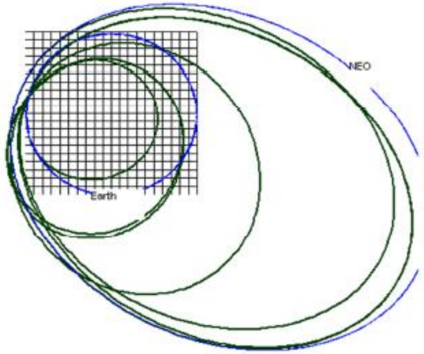
Context – Orbit Transfer Optimisation Software at Airbus Defence and Space

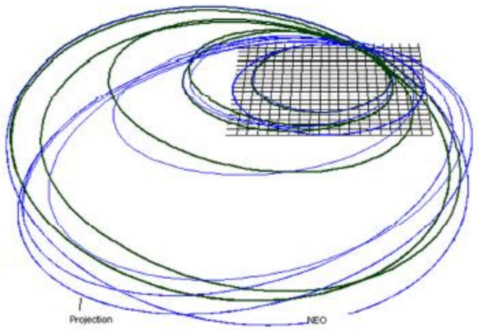
- Orbit transfer optimisation software heritage:
  - QUARTZ:
    - used in operations for Earth bounded chemical transfer optimisation
    - delivered for LEOP and station-keeping in GEO/LEO
  - Optimisation of interplanetary missions
    - with Chemical Propulsion (CP), Electric Propulsion (EP), CP+EP
    - with GA

→Use heritage to develop a multi-revolution low-thrust Earth bounded orbit transfers

QUARTZ







Software Requirements

High Level Requirements

- **Main "original" purpose: optimise low-thrust transfer to GEO orbit**
- **Additional** requirements came along the software development:

Any Earth-bound orbit mission
-LEO
-MEO
-GEO
- Highly eccentric orbits

Any propulsion system
- Low-thrust (EP)
- High or Medium Thrust (CP)
- Hybrid (EP+CP)

Flexibility
- To be used in Mission Analysis and Operations (i.e. for satellite commanding)
- Add/Remove constraints & P/F features easily

Software Requirements

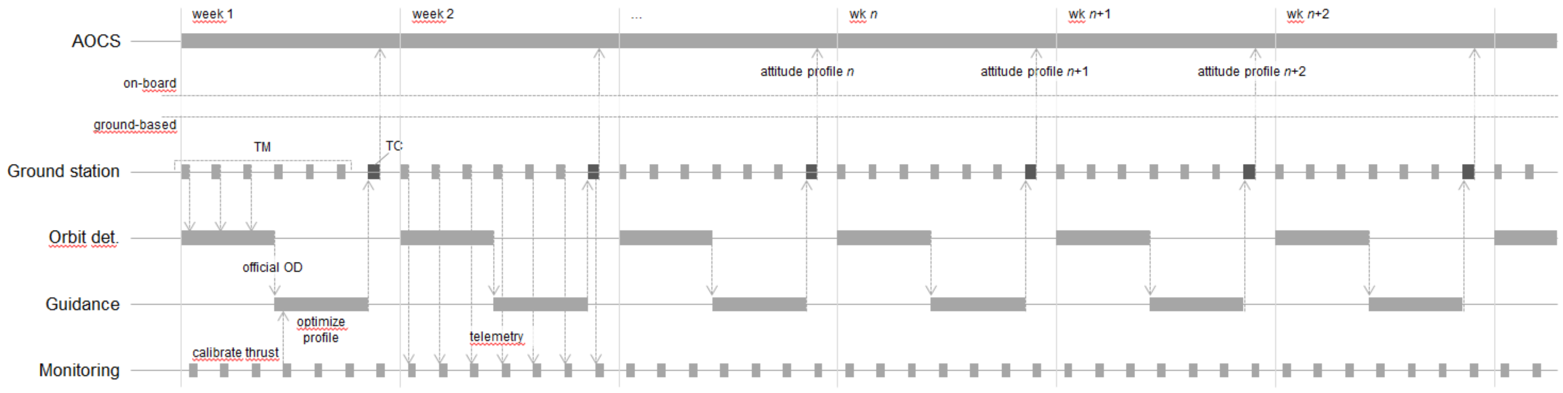
Mission Analysis Requirements

Mission Analysis
▪ Mission Analysis Output - ΔV, transfer duration - S/C att guidance - P/F constraints - Events
▪ Target orbit parameters - Various expressions - Fixed or Upper Bound or Lower Bound
▪ Pareto Front: ΔV vs transfer duration
▪ Optimise injection orbit parameters
▪ Fast run, batch mode, GUI, plots, etc.

Software Requirements

Mission Analysis & Operational Software Requirements

Operations – High Fidelity
▪ Full environment perturbations
▪ Accurate eclipse modeling: - Umbra, penumbra, lightning ratio - Entry & Exit points
▪ Propulsion system – advanced models: - 3 levels (full, reduced, coast) - time-varying functions - thrust orientation in S/C body frame
▪ Accurate battery charge model
▪ Daily use in Operations: - use solution of cycle N-1 as initial guess for cycle N - shall be used by non-expert



Software Requirements

EOR constraints: P/F constraints

Platform Constraints

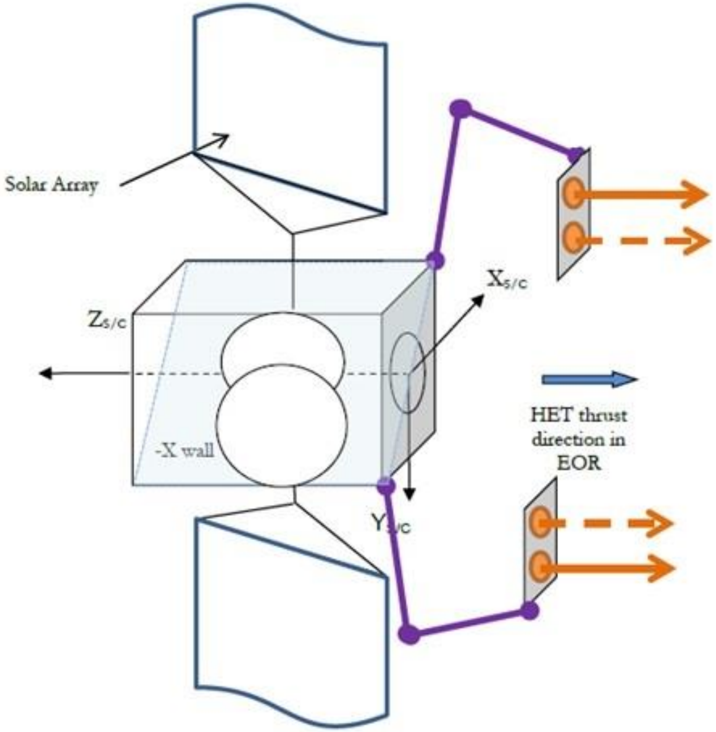
Slew Rates
- *Each S/C axis*
- *Depends on EP level*

Thrust/Coast Duration
- *Min or Max value*
- *CP: burn duration / ΔV / Propellant*
- *EP: thrust or coast*

STR Blinding
- *Avoid blindings*
- *Sun and/or Earth*

Thermal

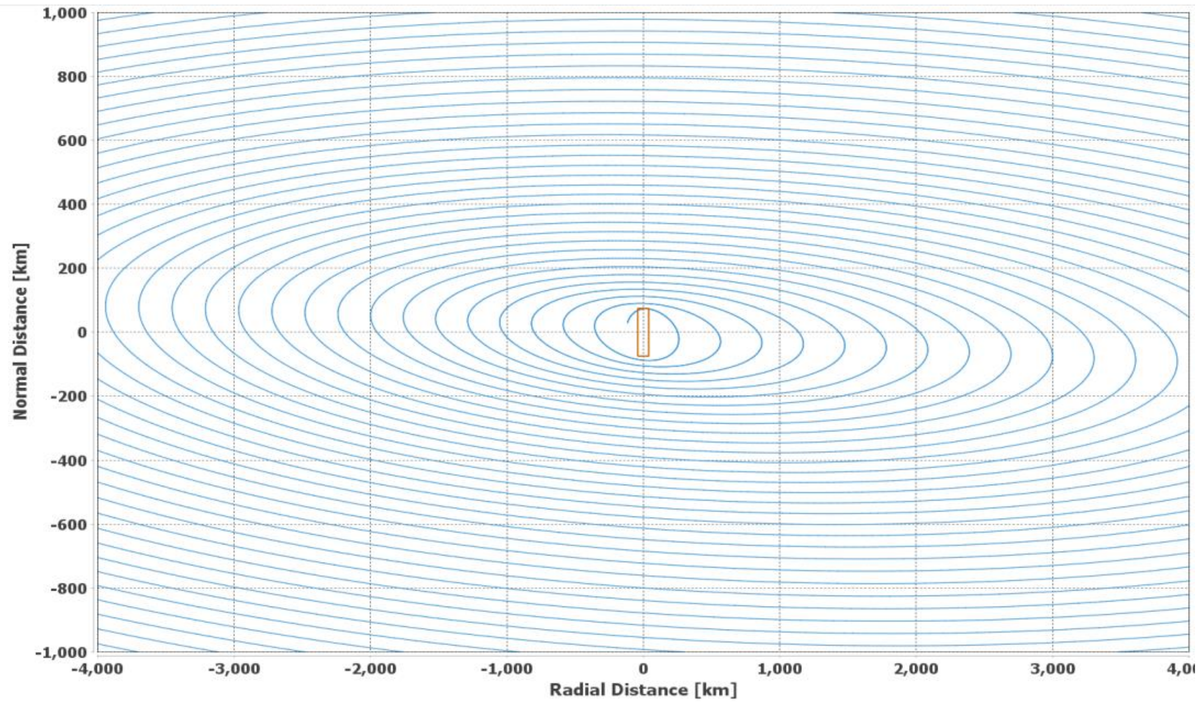
Battery Charge
- *Depth of discharge*
- *Capacity of charge*
- *Solar panels illumination*
- *Reduced thrust or coast*



Software Requirements

EOR constraints: Operational constraints

- Need to model operational constraints during the transfer:
  - Allowing event-type constraints such as:
    - Coast arcs needed for operations
    - Intermediate orbit
  - Chemical burns can be:
    - Fully optimised
    - Set fixed in Inertial Frame or LOF
  - GEO ring avoidance
    - GEO ring model: ΔR and ΔN wrt perfect GEO orbit
    - Constraint: avoid GEO ring for a given time period



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Transfer Optimisation Problem

- Minimise the cost function:

$$J = \phi\big(\boldsymbol{x}(t_0), t_0, \boldsymbol{x}(t_f), t_f; \boldsymbol{p}\big) + \int_{t_0}^{t_f} L(\boldsymbol{x}(t), \boldsymbol{u}(t), t; \boldsymbol{p})\, dt$$

$\boldsymbol{x}$ is the state vector, $\boldsymbol{u}$ is the control vector, t_0 and t_f are the initial time and final time of the trajectory and $\boldsymbol{p}$ some parameters

- Dynamic of the system:

$$\dot{\boldsymbol{x}} = f(\boldsymbol{x}(t), \boldsymbol{u}(t), t; \boldsymbol{p})$$

- Boundary conditions:

$$\psi^0_{min} \le \psi(\boldsymbol{x}(t_0), t_0; \boldsymbol{p}) \le \psi^0_{max} \quad and \quad \psi^f_{min} \le \psi\big(\boldsymbol{x}(t_f), t_f; \boldsymbol{p}\big) \le \psi^f_{max}$$

- Intermediate constraints or event-type constraints:

$$\psi^e_{min} \le \psi(\boldsymbol{x}(t_e), t_e; \boldsymbol{p}) \le \psi^e_{max}$$

- Path constraints:

$$C_{min} \le C(\boldsymbol{x}(t), \boldsymbol{u}(t), t; \boldsymbol{p}) \le C_{max}$$

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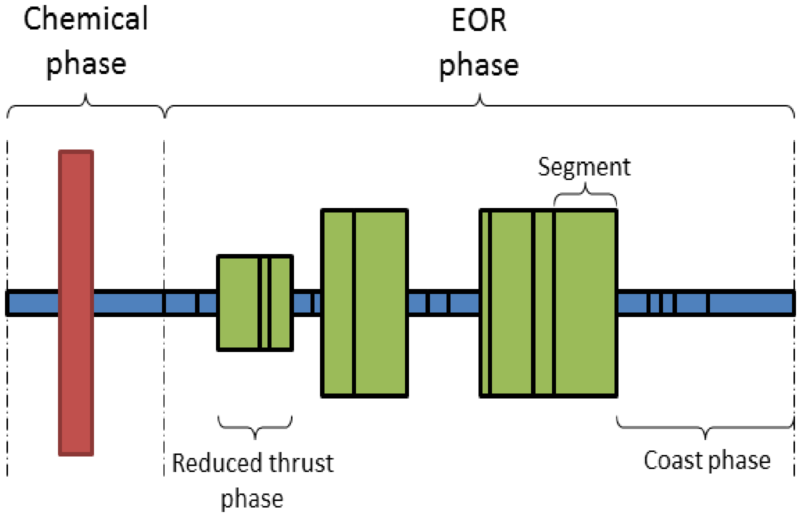
Methodology

- OptElec uses a direct optimisation approach
- Multiple Shooting (MS): discretizes the orbit transfer into segments



- State vector: $\boldsymbol{x} = [X, Y, Z, V_x, V_y, V_z, m]$ or $\boldsymbol{x} = [a, k, h, q, p, L, m]$
- Control variables: $\boldsymbol{u}$ = $(\alpha, \varepsilon, \varphi)$ expressed in inertial ref frame or LOF → azimuth and elevation define the thrust direction

OptElec

Methodology

- The optimisable variables $\boldsymbol{z_i}$ corresponding to the i^{th} segment are defined by:

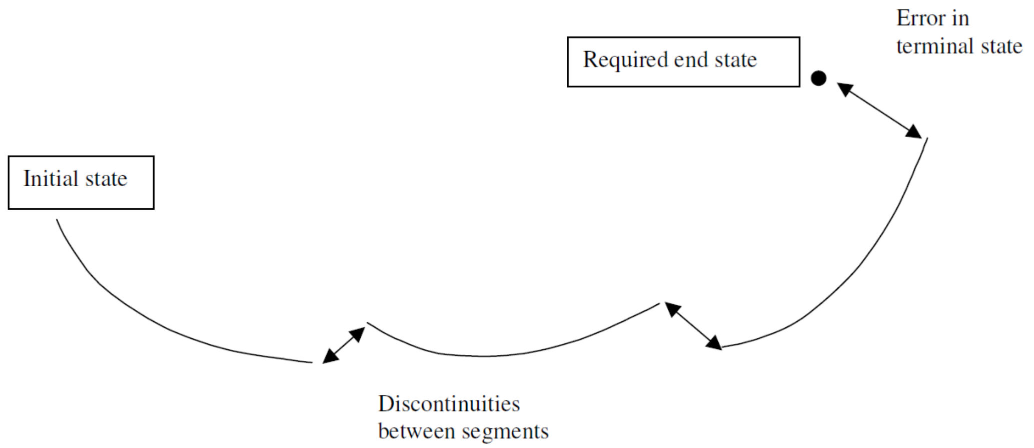
$$\boldsymbol{z_i} = \left[\boldsymbol{x_{i,0}}, \boldsymbol{v_i^{\alpha}}, \boldsymbol{v_i^{\varepsilon}}, \boldsymbol{v_i^{\varphi}}, \boldsymbol{t_i}\right]$$

where:

- $\boldsymbol{x_{i,0}}$ is the state vector at the start time of the i^{th} segment
- $(\boldsymbol{v_i^{\alpha}}, \boldsymbol{v_i^{\varepsilon}}, \boldsymbol{v_i^{\varphi}})$ are the optimizable control parameters corresponding to the az, el and yaw steering angles
- $\boldsymbol{t_i}$ is the time control vector containing the start time and end time

- Constraints
  - Enforce continuity in the trajectory and control
  - Initial + intermediate + terminal constraints
  - Path constraints

- Problem solved using a NLP algorithm



EOR Study Case

Study Case Definition: Hybrid GTO to GEO transfer with high inclination including CP + EP

- Objective:
  - Present a hybrid (CP + low-thrust) transfer case with P/F and operational constraints
  - Show the differences between unconstrained and constrained case
  - Min time and min mass scenarios

- Injection orbit
  - Ha = 35786 km, Hp = 300 km, i = 20 deg, Ω = 90 deg, ω = 180 deg
  - m = 3500 kg
  - Injection date = Jan. 01st 2017, 00h00m

- Target Orbit
  - Drift drift rate = 0.5 deg/day, i = 0 deg, e = 0
  - Geographic longitude = 100 deg East

- Perturbations
  - Earth potential (J_2 and $J_{2,2}$)
  - Luni-solar
  - SRP

- Platform
  - Thrust orientation = [0, 0, 1] in S/C body frame
  - STR orientation = [-0.6, 0.8, 0] in S/C body frame
  - EP (basic model): F = 1.0 N and Isp= 2000 s
  - CP: 2 RCTs providing a thrust F= 10 N each and Isp= 290 s.

EOR Study Case

Study Case – **Minimum Time** Transfer with mixed propulsion systems operational constraints

Case MT0

- Transfer starts with a CP phase using 1 or 2 RCT burns (inertially fixed)
- 1st RCT burn must occur after a minimum of 2 full revolutions after injection
- Maximum allocated propellant mass for this chemical phase is 40 kg
- EOR phase must start on the 5th of January 2017 00h00m

MT1 = MT0 + Battery Charge constraint

- Battery Charge constraint applies when the spacecraft is in eclipse
- Use reduced thrust level (0.5 N available with unchanged Isp)

MT2 = MT1 + operation and P/F constraints

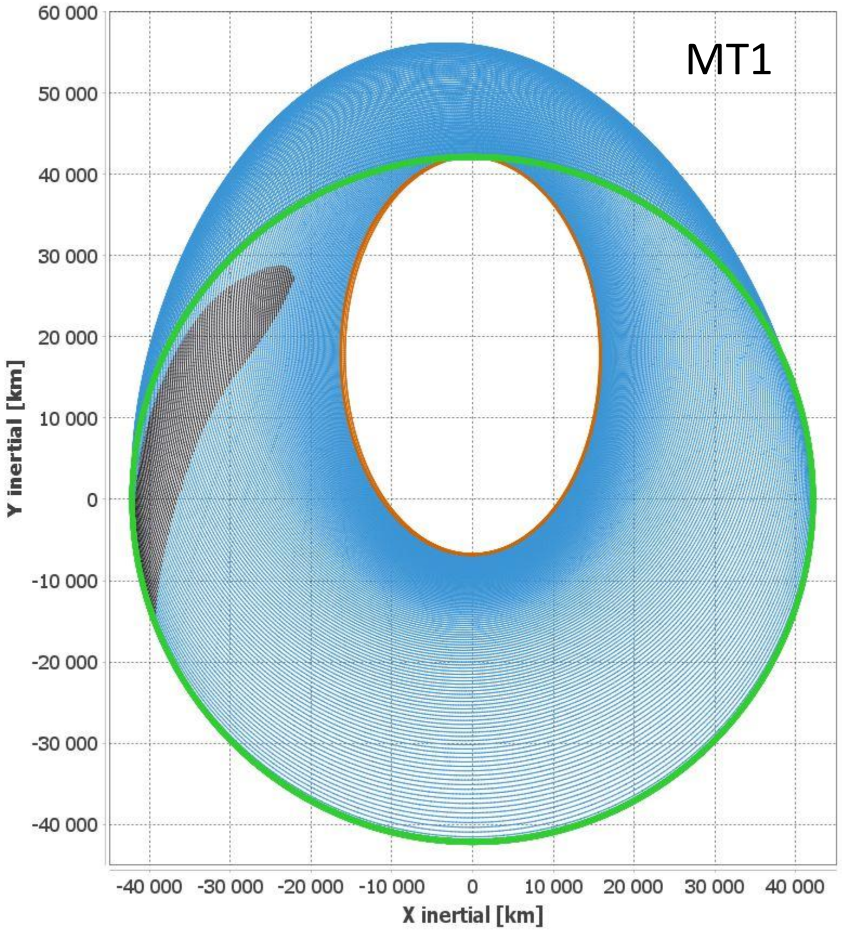
- Min apogee after the CP > 42365 km → a third RCT burn is allowed
- Max slew rates are: 100-200-100 deg/h resp. around X, Y and Z S/C axes
- Sun elevation wrt the S/C X-Z < 30 deg
- No Earth or Sun STR blindings Half angle = 21 deg (Earth) / 26 deg (Sun)
- Any EOR sub-phase (phase with reduced or full low-thrust) ≥ 30 minutes.

EOR Study Case

Study Case – **Minimum Time** Transfer with mixed propulsion systems operational constraints

- Results:
  - For all cases the optimiser uses the 40 kg of CP
  - The CP phase is used by the optimiser to raise the perigee and decrease the inclination
  - The optimum intermediate orbit depends on the Operational scenario (e.g. no thrust in eclipse constraint changes the intermediate Per/Inc)
  - MT2 includes a third burn around the perigee to target the minimum required apogee → less ΔV available for Per/Inc corrections
  - MT1 & MT2 ΔV < MT0 ΔV because reduced thrust located in eclipse → near perigee where thrusting is less efficient
  - Attitude constraint overcost ~ 0.1 %

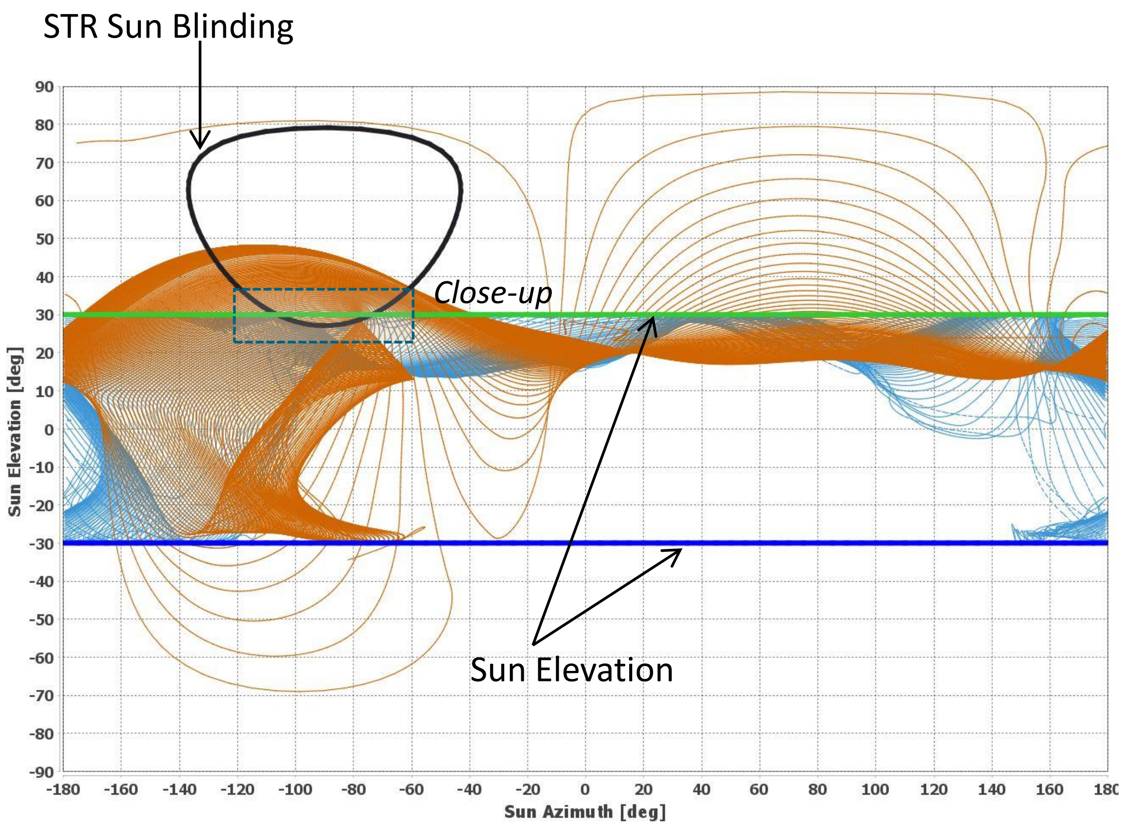
Cases	Transfer Duration [days]	Per alt after CP phase [km]	Inc after CP phase [deg]	ΔV [m/s]	Constraints over-cost [%]
MT0	94.3	524	19.2	2428.2	N/A
MT1	95.7	505	19.1	2417.6	REF
MT2	95.8	498	19.2	2418.4	+0.07

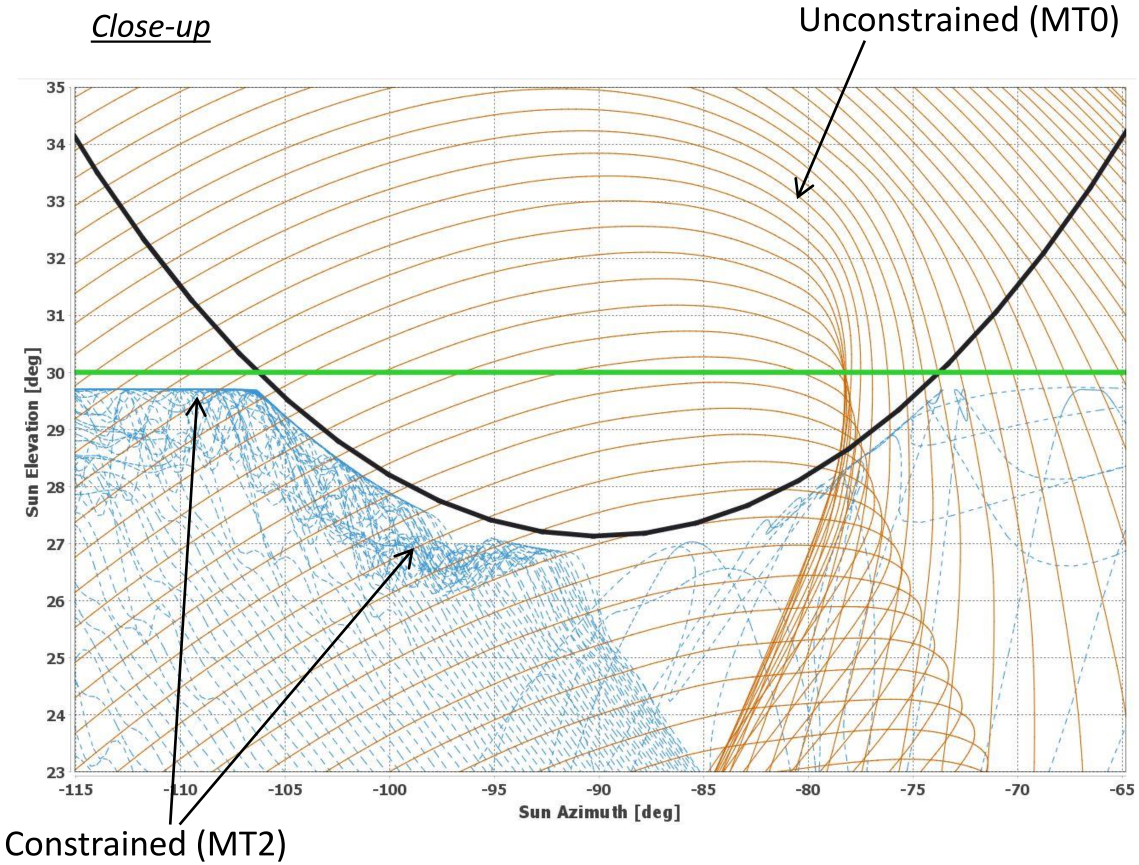


EOR Study Case

Study Case – **Minimum Time** Transfer with mixed propulsion systems operational constraints

- Focus on Sun Elevation + STR Sun blinding constraint:

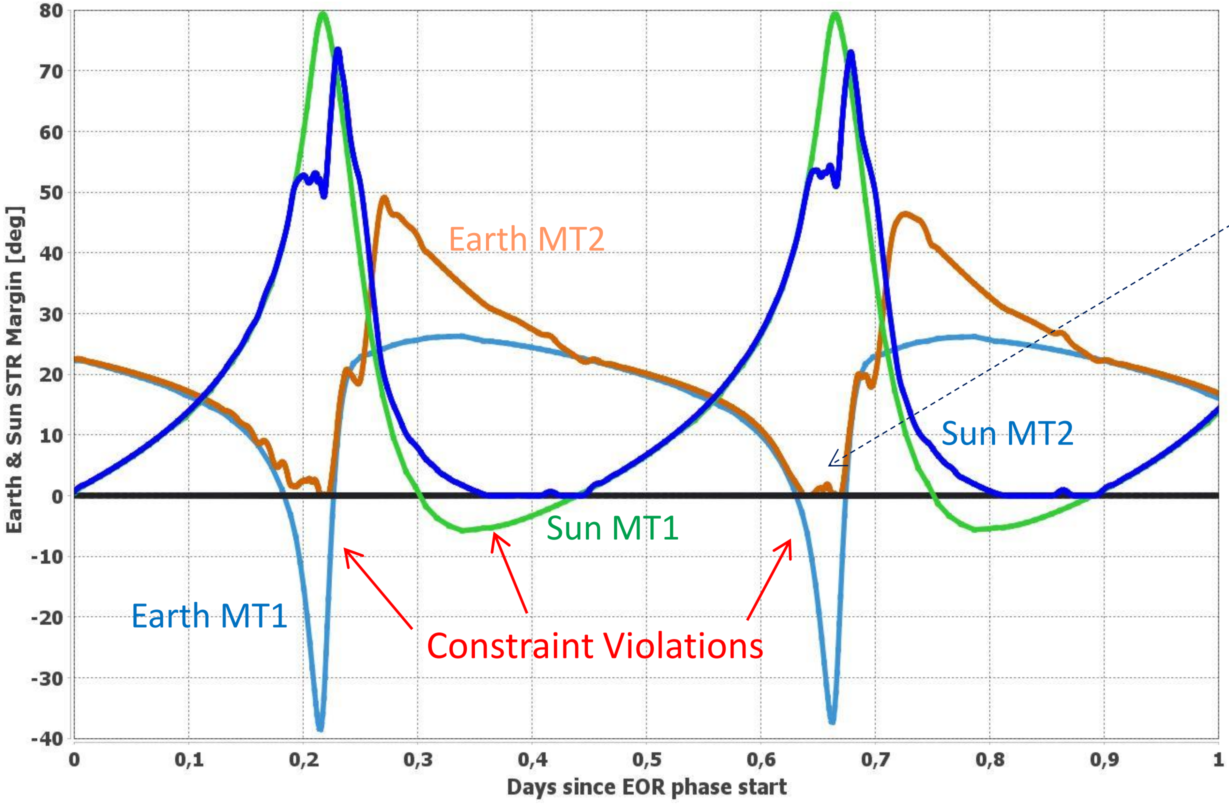




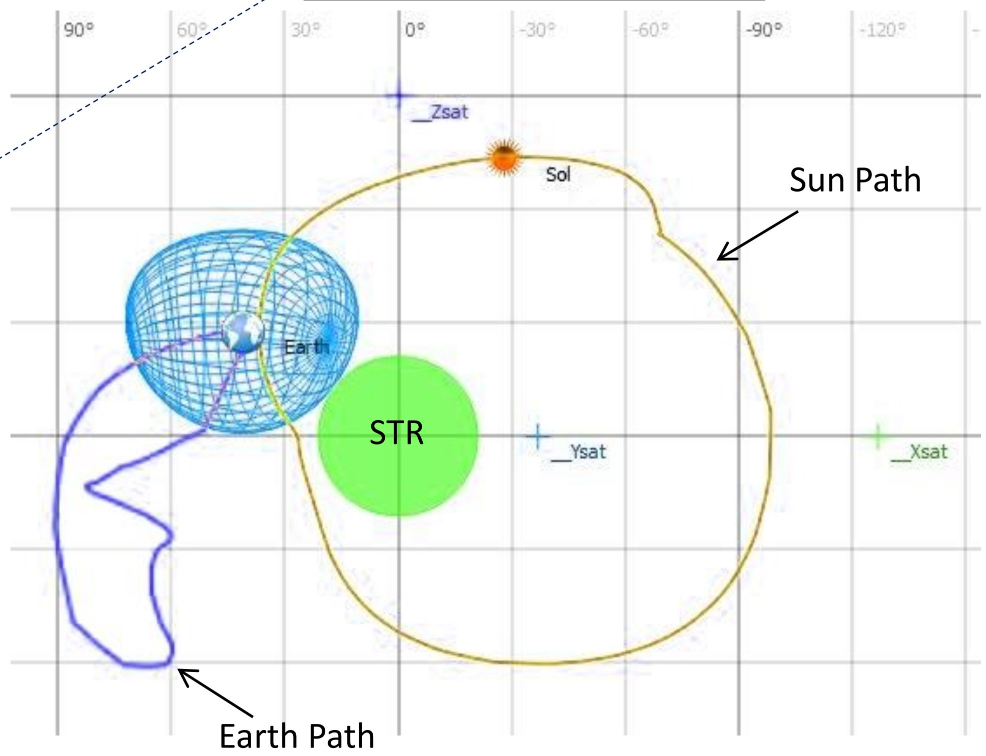
EOR Study Case

Study Case – **Minimum Time** Transfer with mixed propulsion systems operational constraints

- Focus on Sun + Earth STR blinding constraint:



Time = 0.642 days (MT2)



EOR Study Case

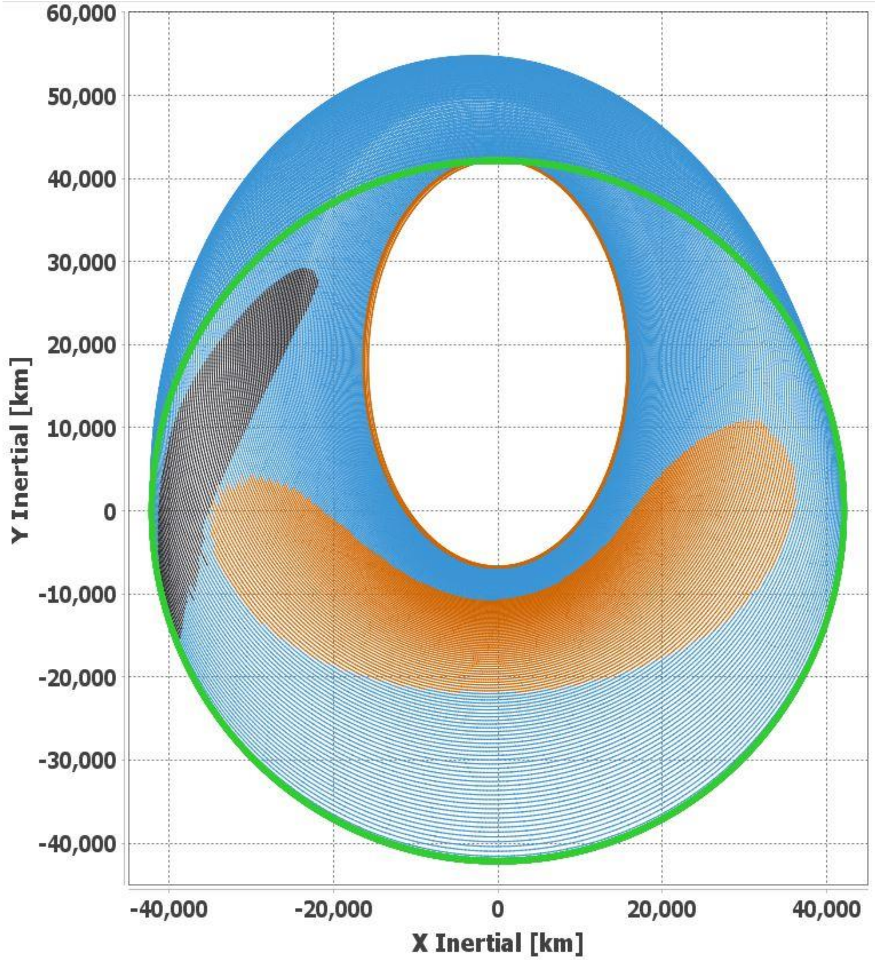
Study Case – **Minimum Mass** Transfer with mixed propulsion systems operational constraints

- Study Case definition:
  - Maximum total transfer duration (including the chemical phase): 100 days
  - Coast arcs authorized during EOR to minimise the propellant usage
  - Reduced thrust must be used when thrusting in eclipse
    → CP + 3 levels of EP (full – reduced – coast)
  - Cases MP1 (resp. MP2) is similar to MT1 (resp. MT2) in terms of operational and platform constraints

Table 4. Summary of the study case results.

Cases	Transfer Type [time/mass]	Transfer duration [days]	ΔV [m/s]	Constraints Over-cost [%]
MT0	Time	94.30	2428.2	N/A
MT1	Time	95.71	2417.6	0.07
MT2	Time	95.78	2418.4	
MP1	Mass	100	2263.1	0.16
MP2	Mass	100	2266.7	

+ ~4 days
-150 m/s !



EOR Study Case

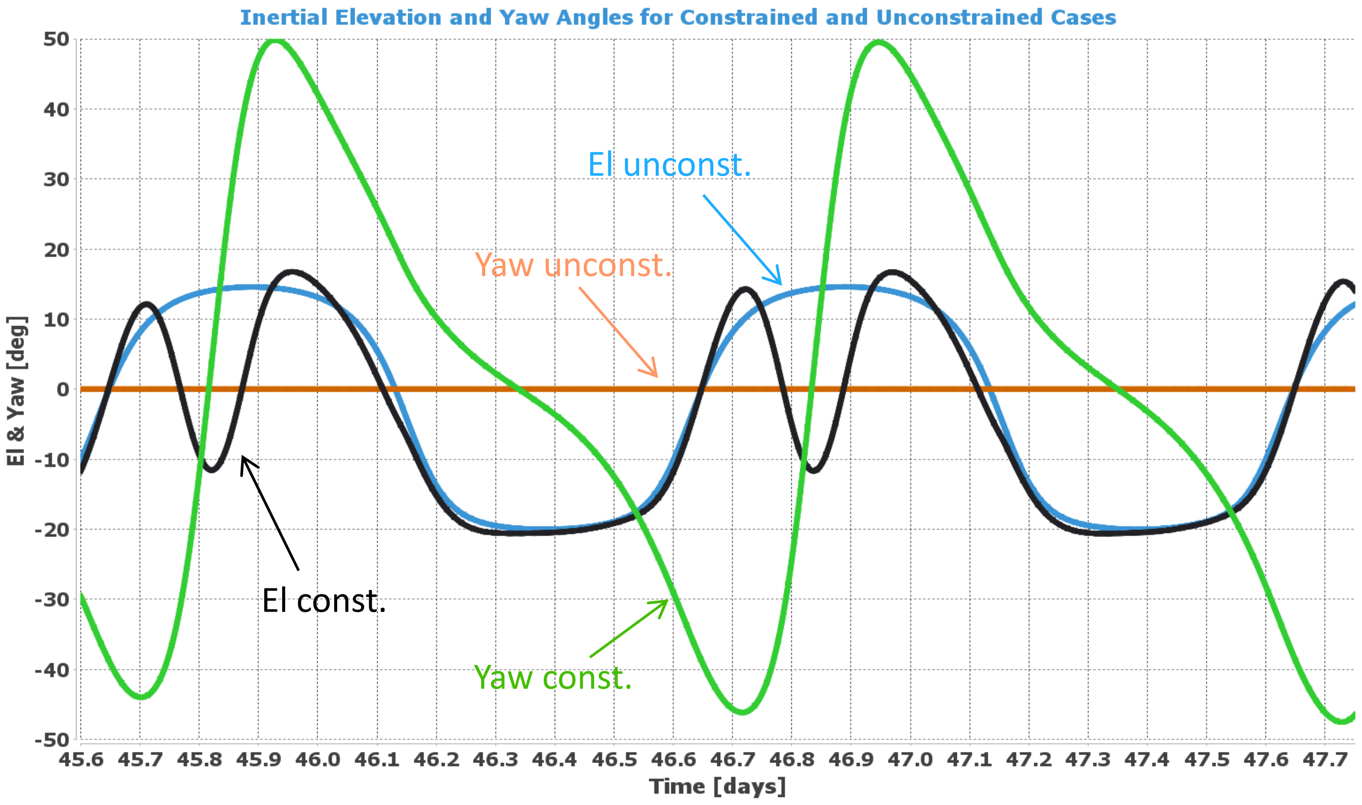
Study Case – Interpretation

- In order to observe all the attitude and slew rate constraints, the optimiser uses in priority the remaining degree of freedom, i.e. the rotation around the Zsat axis but it may also be forced to change the thrust steering angles

- The over-cost remains limited

→Evaluated during Mission Analysis

→If needed, the over-cost can be compensated by slightly increasing the allowed maximum transfer duration



Chemical Study Case

Operational Study Case Definition & Results

- Assumptions
  - **Initial orbit**: ha = 28900 km, hp = 290 km, i = 28 deg
  - CPS: F= 450N, Isp= 320 s

  target: - Drift = 1 deg/day , i = 0.1 deg, Ω = 270 deg, $lgeo$= 0 deg
  - Max apogee radius: 42125 km
- Manoeuvres – Mission Analysis
  - 2 maneuvers at perigee (PVA) followed by 3 maneuvers at apogee (AEF)
  - Manoeuvre sequence: 5-3-2.5-2-2 (number of revs between subsequent manoeuvres) + the last burn (AEF) must not exceed 350 m/s.
- P/F constraints
  - AEFs fixed in inertial frame but PVA may have time-varying thrust direction.
  - Max burn duration (2 h) // Min burn durations (120 s)

- Results

Table 5. Comparison of the optimised chemical transfers.

Cases	AoP at injection		Last ΔV		Total ΔV [m/s]
	Status	AoP [deg]	Status	ΔV [m/s]	
C1	Fixed	180	Max	350	1974.2
C2	Fixed	180	Free	468.9	1972.3
C3	Free	176.18	Max	350	1959.2

Max last ΔV size relaxed

Optimise AoP at injection

To the Moon…

Study Case Definition

- Software upgrade:
  - Central gravity field can be chosen (Earth, Moon, other planets)
  - Initial and target orbit expressed in the ref frame of choice
  - Applications: low-thrust planetary escape or insertion

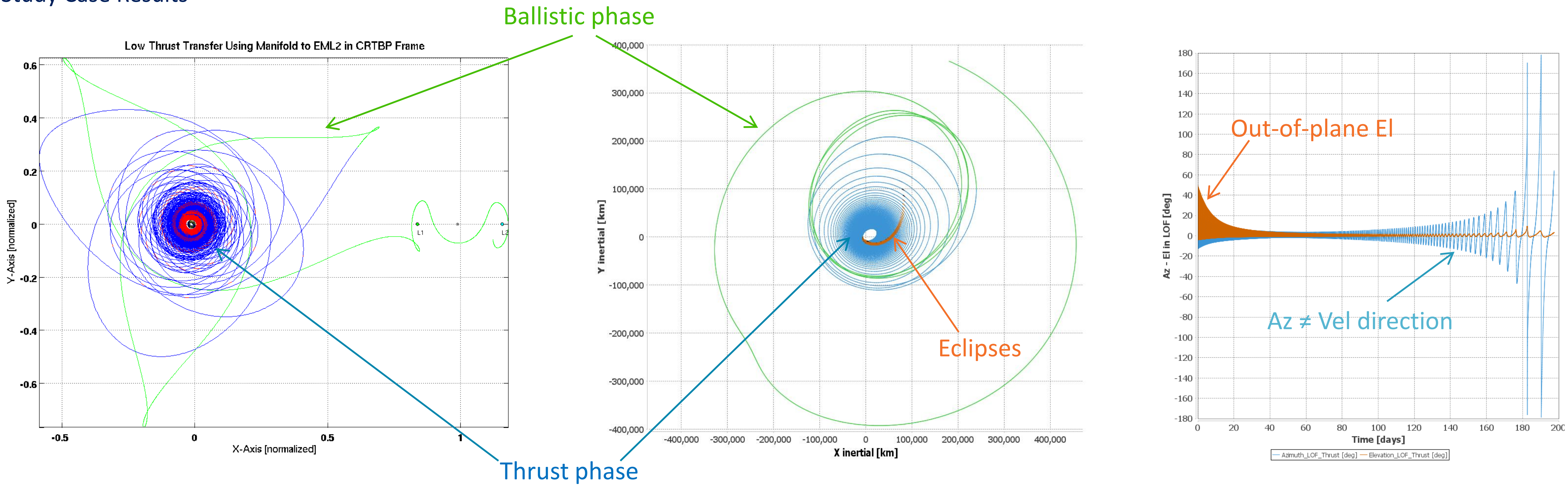
- Ex: Application to the Earth-Moon (EML2 Halo orbit) transfer
  - Phase 1: low-thrust spiraling up to stable manifold entry
  - Phase 2: ballistic phase along the stable manifold

- Here the approach consists in:
  - Fixing the stable manifold « entry point »
  - Optimising the low-thrust phase under constraints

- Initial orbit: sub-GTO orbit (Ha = 20000 km, Hp = 200 km and Inc = 28 deg)
- Constraints: max slew rate + thermal + battery charge
- Earth harmonics (J_2) + Moon + Sun + SRP

To the Moon…

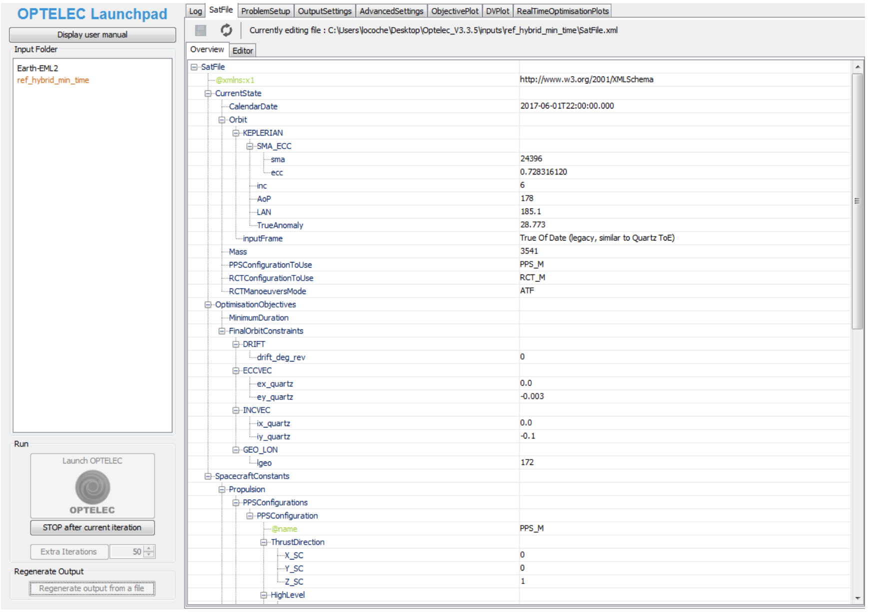
Study Case Results

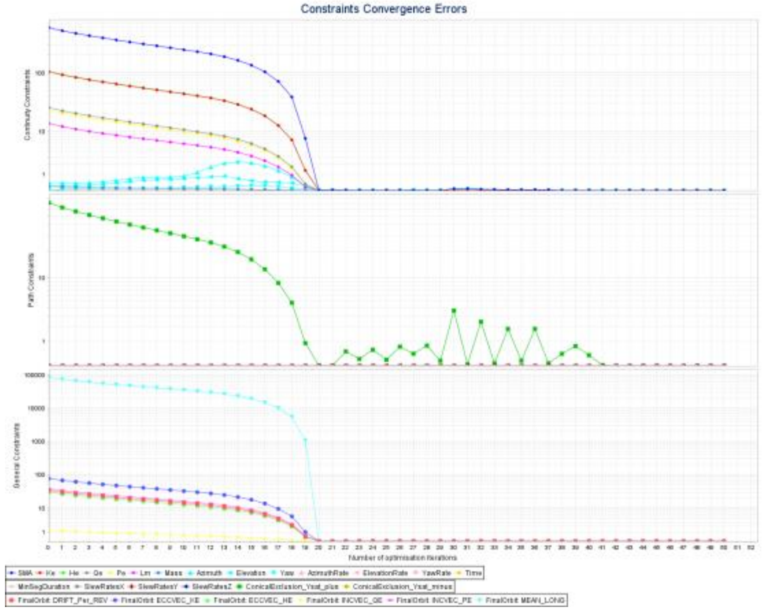


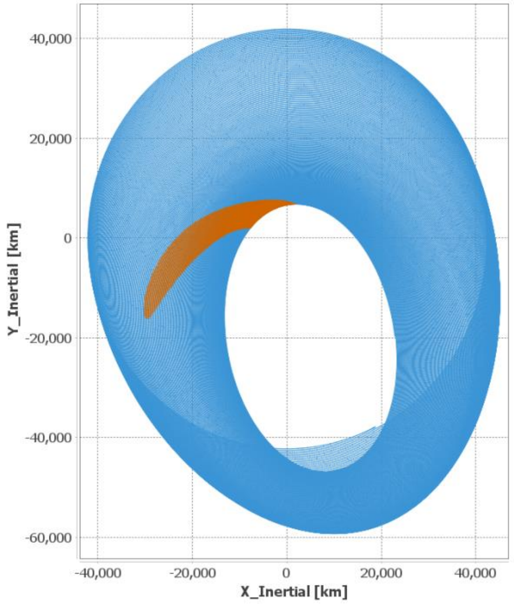
- Step forward: a more « global » optimisation → e.g. for a given Az of the Halo orbit, optimise:
  - Initial position on the Halo orbit
  - Stable manifold backward propagation duration
  - Low-thrust transfer phase including coast arcs if needed → should enable to find new solutions
- Further step: Whole transfert in the full ephemeris + include P/F and operational constraints

Conclusions

- One single tool for Mission Analysis and Operations
- Include P/F and operational constraints
- Treat all Earth-bounded orbit and propulsion configuration cases
- Can be extended to treat Earth-Moon, planetary insertion/escape cases
- The S/W architecture is common to all cases – only the optimisation settings change via a configuration file
- Used during P/F design (since 2012), Mission Analysis (2014) and in operations since 2017: 3 EOR (incl. degraded case) + 3 Chemical Propulsion transfers!







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Validation

- **Minimum time transfers** *(taken from [Betts] & [Kluever])*
  - includes J2
  - thrust OFF in eclipse
  - LEO to GEO & GTO to GEO cases

→Consistent results wrt Ref

Table 1. Ref case definition.

Cases	Perturb	F [N]	Isp [s]	Mass [kg]	Sma [km]	Ecc [-]	Inc [deg]
1	-	0.35	2000	2000	24509	0.725	7
2	J2, thrust OFF in eclipse	1.86948	1800	5500	6780	0	5.2
3		0.40171	3300	1200	6927	0	28.5
4		0.20085	3300	450	24364	0.731	27

Table 2. Minimum-time EOR validation.

Cases	Mission	References	Transfer duration (days) Ref	Transfer duration (days) OptElec
1	GTO-GEO	MIPELEC [9]	137.5	137.4
2	LEO-GEO	Ref [6]	167.8	167.7
3	LEO-GEO		198.8	199.2
4	GTO-GEO		66.6	66.7

- **Minimum mass transfers** *[Krier]*:

ha=35786 km

hp=300 km

i=6 deg

Ω=270 deg

ω=180 deg

→ Consistent results wrt Ref